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## **Comparing three different methods to model scenarios of future glacier change in the Swiss Alps**

Linsbauer, Andreas ; Paul, Frank ; Machguth, Horst ; Haeberli, Wilfried

**Abstract:** Ongoing atmospheric warming causes rapid shrinking of glaciers in the European Alps, with a high chance of their near-complete disappearance by the end of the 21st century. Here we present a comparison of three independent approaches to model the possible evolution of the glaciers in the Swiss Alps over the 21st century. The models have different levels of complexity, work at a regional scale and are forced with three scenarios of temperature increase (low, moderate, high). The moderate climate scenario gives an increase in air temperature of 28C and 48C for the two scenario periods 2021–50 and 2070–99, respectively, resulting in an area loss of 60–80% by 2100. In reality, the shrinkage could be even faster, as the observed mean annual thickness loss is already stronger than the modelled one. The three approaches lead to rather similar results with respect to the overall long-term evolution. The choice of climate scenarios produces the largest spread (40%) in the final area loss, while the uncertainty in present-day ice-thickness estimation causes about half this spread.

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# Comparing three different methods to model scenarios of future glacier change in the Swiss Alps

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**ABSTRACT.** The ongoing atmospheric warming causes rapid shrinking of glaciers in the Alps with a high chance of their near-complete disappearance by the end of the 21st century. We here present a comparison of three independent approaches, to model the possible evolution of the glaciers in the Swiss Alps over the 21st century. The models have different levels of complexity, work at a regional scale and are forced with three scenarios of temperature increase (low, moderate, high). The moderate climate scenario give an increase in air temperature of about 2 and 4°C for the two scenario periods centred around 2035 and 2085, respectively, resulting in an area loss between 60 and 80% by 2100. In reality, the shrinkage could be even faster, as the observed mean annual thickness loss is already stronger than the modelled one. The three approaches lead to rather similar results with respect to the overall long-term evolution. The choice of climate scenarios produces the largest spread (about 40%) in the final area loss, while the uncertainty in present-day ice-thickness estimation causes about half this spread.

## INTRODUCTION

The ongoing glacier shrinkage in the Alps is of increasing interest, for the expected changes in the hydrologic regime of major river catchments (e.g. Huss, 2011; Mauser and Bach, 2009) as well as for its influence on hydropower production (e.g. Schaeffli

and others, 2007; Terrier and others, 2011; Farinotti and others, 2012), tourism (Fischer and others, 2011), and natural hazards (e.g. Moore and others, 2009; Frey and others, 2010; Haeberli and others, 2010; Künzler and others, 2010). Scenarios of future climate change with further increasing temperatures (IPCC, 2007) involve continued if not accelerated glacier shrinkage and may even cause the complete loss of glaciers in entire mountain ranges (e.g. Zemp and others, 2006). Several methods – based on different basic concepts, complexity and application scales – have been developed to determine future glacier evolution (i.e. change in glacier area and/or volume) along with the related changes in runoff. Such glacier models can either be regionally calibrated empirical-statistical models or process-oriented models, which are more physically based (Hoelzle and others, 2005).

For modelling glacier evolution at the scale of entire mountain ranges, a variety of simple techniques and approaches – requiring only few input data – have been applied in the past. Examples are a shift of the equilibrium line altitude (ELA) according to given changes in temperature and/or precipitation and the related change of the accumulation area (e.g. Lie and others, 2003; Zemp and others, 2006; Condom and others, 2007; Paul and others, 2007), the application of various spatio-temporal extrapolation techniques (Huss, 2012) or the parameterization scheme for glacier inventory data introduced by Haeberli and Hoelzle (1995). Using even more simplified methods, future glacier changes are also modelled at a global scale, e.g. to assess the future contribution of glaciers to sea-level rise, mostly as a combination of analogy concepts and multivariate analysis with strongly abstracted glaciers (e.g., Raper and Braithwaite, 2005; Marzeion and others, 2012; Bahr and others, 2009). Radic and Hock (2011) and Raper and others (2000) considered the change in a standardized area-elevation distribution (hypsometry) to account for the adjustment of glacier area to future climate conditions. A more direct way to determine future glacier evolution is the calculation of glacier volume loss based on observed overall changes in glacier thickness as derived from geodetic measurements (e.g. differencing of two digital elevation models) over a longer time period (e.g. Huss and others, 2010b). Based on these observations simple parameterizations of thickness evolution can be derived and – in combination with calculated ice thickness distributions (e.g., Farinotti and others, 2009; Linsbauer and others, 2012) and mass balances (e.g., Giesen and Oerlemans, 2012) – be applied to large glacier samples (e.g., Huss, 2011; Salzmann and others, 2012; Machguth and others, submitted).

A variety of more complex approaches exist to model future glacier evolution, based on mass balance modelling and glacier flow (e.g., Le Meur and others, 2007; Juvet and others, 2009, 2011). These models are computationally expensive and only applicable to individual and well studied glaciers, where sufficient data (also for calibration and validation) exist.

Ultimately, the glacier evolution models described above must be linked to a climate scenario and changes should be time-dependent. Although models that are based on mass balance calculations can be directly linked to climate model output (e.g. Machguth and others, 2009), the modelled mass change is not identical to thickness change, as the geometric adjustment of a glacier (change in area or length) to a mass balance forcing will only occur after a delay. Using a (surface) mass balance model

to determine future glacier evolution has thus to implement a parameterization of mass transport. This can be obtained by a comparison of the modelled cumulative mass budget and the observed overall volume loss over the same period (Huss and others, 2010b). For the simpler approaches (e.g. shift in the ELA) the link to a certain climate scenario can be established based on atmospheric lapse rates or known relations between ELA change and changes in temperature, precipitation and the energy balance (e.g. Kuhn, 1981). However, the involved time-dependence of the geometric adjustment has to be introduced artificially, e.g. based on estimated response times for larger glacier samples (e.g. Haeberli and Hoelzle, 1995).

Although the various existing approaches have structurally different designs and use different climate forcings, they tend to provide similar results. A model intercomparison can help to tease out model-specific problems and hence sources of uncertainty for simulations and predictions. Thereby, the boundary conditions for the compared approaches are usually held constant and the models compared are conceptually rather similar. Models that use conceptually different approaches have so far not been analysed together. In this sense, we here compare three methods with different complexity but being all applicable to large glacier samples, using the example of the glaciers in the Swiss Alps.

One model (**M1**, cf. section 3.1) provides future glacier area only and is based on an adjustment of the hypsometric area distribution following an upward shift of the ELA (Paul and others, 2007) according to three scenarios of climate change.

A second approach (**M2**, cf. section 3.2) uses modelled ice thickness distribution in combination with observed geodetic volume changes for an extrapolation of the elevation-dependent thickness change and related area evolution into the future, assuming a constant rate of ice thickness loss as a reaction to temperature increasing by  $1^{\circ}\text{C}$  in time steps of 20, 25 and 30 years.

A third method (**M3**, cf. section 3.3) uses a distributed mass balance model that is directly coupled to three ensembles of downscaled, de-biased, gridded and transient regional climate model (RCM) simulations (Machguth and others, 2009, 2012; Salzmann and others, 2012) in combination with a hypsometric change in glacier geometry using the parameterization by Huss and others (2010b).

Besides comparing the modelled glacier extents, hypsometric distributions and relative area loss for M1, M2 and M3, we also analysed the uncertainties introduced by model simplifications, the ice thickness estimations and the climate change scenarios. Because future glacier extents or runoff from glacierized catchments cannot be validated, a validation can only be performed over the recent past. We have thus compared the modelled area and/or volume changes over the 1985–2000 period with the observed ones, being well aware that all three models are not designed to give reliable results over such a short time scale.

## STUDY REGION AND DATA

The study region of the Swiss Alps comprises an area of roughly 25'000 km<sup>2</sup> including a glacierized area of about 1300 km<sup>2</sup> in 1973 (Müller and others, 1976) (Fig. 1). The Digital Elevation Model (DEM) covering the study site was produced by the Swiss Federal Office of Topography (swisstopo), has a cell size of 25 m (named DEM25 in the following) and represents approximately the glacier surfaces around 1985 (Rickenbacher, 1998; swisstopo, 2005). The accuracy of the DEM25 is reported to be 2.5–7.5 m in horizontal direction and less than 10 m in vertical direction (swisstopo, 2005). The digital glacier outlines are based on the digitized Swiss Glacier Inventory from 1973 (SGI1973) by Müller and others (1976), in the revised version by Maisch and others (2000) and includes 2365 glacier and glacierets larger than 0.01 km<sup>2</sup>. These glacier polygons fit well to the glacier extent in the DEM25, as only small overall area changes took place for most glaciers in the Alps between 1973 and 1985 (Paul and others, 2004). While the first two models (M1 and M2) were applied to all glaciers of the Swiss Alps, M3 was restricted to a sample of 101 selected glaciers as explained in section 3.3, representing roughly 50% of the total glacierized area and 75% of the ice-volume in Switzerland.

→ **Fig. 1 (overview) about here**

The ice thickness distribution for all Swiss glaciers is calculated with the GlabTop model as described in Paul and Linsbauer (2012) and Linsbauer and others (2012) using the DEM25 and the glacier outlines from the SGI1973 as an input. GlabTop spatially extrapolates locally (50 m elevation bins) estimated glacier thickness values that are derived from averaged values of surface slope and a mean basal shear stress per glacier (assuming perfect plasticity, cf. Paterson, 1994). The basal shear stress was empirically derived from glacier elevation range which can be seen as a proxy for mass turnover (Haeberli and Hoelzle, 1995), and has an upper-bound value of 150 kPa for glaciers exceeding an elevation range of 1.6 km (cf. Li and others, 2012). The obtained model results have an uncertainty range of about  $\pm 30\%$ , as shown by a comparison with independent radar profiles and an uncertainty analysis (Linsbauer and others, 2012).

The presence of glaciers, their number and characteristics are mainly linked to the elevation of their headwater catchment which determines the seasonality of the runoff regime (mostly pluvio-nival or glacio-nival). Most Swiss glaciers (exceptions are found in the Val Bregaglia and the Val Fenga) are drained by seven major river catchments with gauging stations in the lowlands. In combination with the outlines of these major river catchments, the grid from the DEM differencing (Shuttle Radar Topography Mission DEM (SRTM3)–DEM25) from the study by Paul and Haeberli (2008) was used to obtain catchment-specific elevation changes over the 1985 to 1999 period based on zone statistics (with each major river catchment as a zone). Apart from a few regions with data voids over glaciers, this data set covers nearly all glaciers in the Swiss Alps. The mean change of the DEM differencing (-11 m w.e.) is in good agreement with the mean cumulative mass budget of nine Alpine glaciers with measured mass balances (-10.8 m w.e.).

Both, the reported temperature data from Rebetez and Reinhard (2008) and the measured temperatures from 13 selected weather stations (cf. Fig. 2) run by the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) show a distinct temperature increase of about  $1^{\circ}\text{C}$  between 1980 and 1995. From the 1990s until present the temperatures further increased (by about  $0.5^{\circ}\text{C}$ ), but at a lower rate (Fig. 2).

→ **Fig. 2 (temperature) about here**

The climate scenarios for all three models used are either based on these observed temperature changes (M1, M2) or downscaled RCM simulations (M1, M3) from the EU-*ENSEMBLES* program (van der Linden and Mitchell, 2009). All climate model chains (combinations of a general circulation model (GCM) and an RCM) use the A1B emission scenario (IPCC, 2007), cover the period 1951–2099 and have a grid size of 25 km.

The three climate scenarios which force model M1 are based on the work of Bosshard and others (2011), where values for temperature and precipitation for various MeteoSwiss weather stations were downscaled using a delta change approach for the scenario periods 2021–2050 and 2070–2099 (relative to the control period 1980–2009), based on ten climate model chains from the *ENSEMBLES* project. The scenarios for the ELA step changes are based on the mean values of all ten model chains for both scenario periods and all 13 selected MeteoSwiss weather stations. As in the control period the temperatures already increased by  $1^{\circ}\text{C}$  this temperature step is also considered.

Model M2 follows three linear trend extrapolations, where it is assumed that the mentioned temperature increase of  $1^{\circ}\text{C}$  is repeated every 20, 25 or 30 years, resulting in three different scenarios. The moderate scenario projects an increase in air temperature of  $2/4^{\circ}\text{C}$  for the two scenario periods centred around 2035 and 2085. The 25 years repeating time is thus half as long as the temporal difference between the scenario periods. The 20 and 30 year steps results from extrapolations fitted to the lower and upper values of the modelled variability of the 13 MeteoSwiss weather stations. With these values the temperature increases in M2 are close to the ones resulting from the climate scenarios of M1 and M3 (Fig. 2). The distributed mass balance model in M3 is directly forced with three ensemble means of the A1B scenario using RCM simulations from *ENSEMBLES*, assuming ensemble means to be the most plausible scenario guess (e.g. Guo and others, 2007). Ensemble E7m consists of seven different RCMs realizations (driven from ECHAM5-r3, HadCM3Q0 and the Arpege GCMs), E4m consists of four RCMs all driven with ECHAM5-r3 and E2m is the ensemble of the two HadCM3Q0 driven ensembles (Salzmann and others, 2012). Monthly resolution RCM grids were chosen because the daily resolution grids showed unrealistic variability in daily precipitation.

The climate model input datasets are thus different by source, but not by value (Fig. 2). The moderate scenarios from M1 and M2 as well as E7m from M3 (the moderate scenario used in this model) project a  $2/4^{\circ}\text{C}$  temperature increase for the two scenario periods centred around 2035 and 2085.

## METHODS

For all three models, the initial glacier extent is given by the glacier outlines from 1973 (SGI1973; Maisch and others, 2000) and the swisstopo DEM25 with 25 m resolution, referring to the glacier surfaces at around 1985. The starting point 1973/1985 was chosen as most glaciers were rather close to a dynamic steady-state then. The required ice thickness distribution for two models (M2 and M3) is taken from Linsbauer and others (2012).

### ELA-Shift Model (M1)

The ELA-shift model is described in Paul and others (2007) and thus only shortly repeated here. The model is based on the fact that with rising temperatures the ELA of glaciers is shifted to higher elevations (here by  $150 \text{ mK}^{-1}$ , cf. Kuhn, 1981), resulting in smaller accumulation areas and, after some time, smaller glacier extents. Using a balanced budget accumulation area ratio ( $\text{AAR}_0$ ) of 60% (WGMS, 2011), new total glacier sizes can be calculated and adjusted by removing the lower-most parts of a glacier. This model only provides information on how large glaciers will be after full adjustment without saying when this will happen. To link the glacier adjustment to a time scale considering that response times vary from about 5 to maybe 100 years or more, the same mean response time of 50 years (Haeberli and Hoelzle, 1995) is assumed for all glaciers. This matches the years 2035 and 2085, the centred scenario periods when starting from 1985. In order to have model results in 5-year time steps, the total area change over the 50-year response time was divided into ten single steps.

There are several restrictions to the validity of the model due to the simplicity of the approach. The model calculates new glacier extents for given ELA-shifts and a hypothetical new steady-state. However, equilibrium is not reached in reality as the climate is in constant change and glaciers continuously adjust their extents to new climatic conditions depending on their specific geometry and response times. With a constant 50-year response time for all glaciers, the speed of area change is overestimated for the largest and underestimated for small glaciers. As this approach works in two dimensions only, the introduced response time only serves for adjustment of the area (thickness changes are not considered) to make the method time-dependent. Moreover, the balanced budget  $\text{AAR}_0$  might vary between 50 and 70% for individual glaciers (Machguth and others, 2012), whilst here it is assumed to be constant and the same for all glaciers.

M1 is coupled with climate in a retrospective manner. The 50 years response time period for all glaciers is starting in 1985 (running to 2035 and 2085 in the model). In the first period all glaciers react to the  $1^\circ\text{C}$  temperature increase of the mid-1980s (cf. Fig. 2 and Rebetez and Reinhard, 2008) that resulted in a 150 m increase of the ELA. In the second period the glaciers react to the warming of the first 50 years according to three different temperature scenarios. These scenarios are derived from the means of the delta change values from ten RCM models yielding an increase in ELA of +100 m (low temperature scenario), +200 m (moderate), and +300 m (high). So it is a step-change and retrospective response model, i.e. reacting to a forcing that

has taken place in the past. The 5-year time steps are only used to generate a smooth transition between the two steady-state extents.

## Thickness Change Parameterization (M2)

Since the beginning of the 1980s increasingly negative glacier mass balances were observed in the Alps (WGMS, 2011). The related thickness change for the period from 1985 to 1999 was calculated for all Swiss glaciers from DEM differencing (Paul and Haeberli, 2008), revealing strong thickness losses for low-lying and flat glacier tongues. This illustrates that the adaptation of the glacier extent to a rapidly changing climate can be dominated by thickness loss (downwasting) rather than area change (Huss and others, 2008, 2010b). Plotting thickness loss vs. altitude for the major river catchments reveals a rather similar and increasing thickness loss towards lower elevations for all regions (Fig. 3). To parameterize this for the entire study region, we used similarly to Huss and others (2010b) an empirically derived elevation dependent function as an average for catchment related mean values composed of a lower (below 2000 m) linear decline and an upper (above 2000 m) quadratic decrease:

$$dh/dt = \begin{cases} -70 + (DEM_i - 1300) \cdot \frac{54}{700} & \text{if } DEM_i \leq 2000 \\ -16 + \frac{(DEM_i - 2000)^{1/2}}{3.125} & \text{if } DEM_i > 2000 \end{cases} \quad (1)$$

with  $dh/dt$  the rate of thickness change (m/year) within the specified time period and  $DEM_i$  the elevation (m.a.s.l.) of each grid cell. Of course, the assumption that all glaciers are subject to the same elevation-dependent thinning rates is not correct (e.g. delay due to debris cover or different shading conditions) and the resulting area changes can be strongly over- or under-estimated for individual glaciers. Above 3000 m the approximation of the parameterization differs from the extracted thickness loss rates in Fig. 3, but values in this elevation range are influenced by artefacts in the SRTM3 DEM. The decrease to zero at the highest elevations is implemented to keep small, steep and thus thin glaciers at high elevations from disappearing too fast. The used function is an empirical one rather than derived by a regression to better accommodate with the DEM uncertainties and model needs mentioned above. In this regard it has to be stressed that the modelled area changes are assumed to be realistic only at the regional scale (e.g. for major river catchments).

→ **Fig. 3 (parameterization) about here**

M2 is coupled with climate (a) by relating the observed thickness change from 1985 to 1999 to the observed temperature increase of 1°C mentioned above and (b) by assuming that the glacier surface will adjust to this forcing over a 20, 25 or 30 year time period (Fig. 2). This trend is then assumed to continue into the future (linear extrapolation) resulting in a 1°C temperature increase every 20, 25 and 30 years. Glacier area is removed once the cumulative ice thickness loss is getting higher than the initial ice thickness. Each time the thickness change increment is subtracted from the initial DEM, the glacier surface gradually shifts to lower elevations where the thickness loss is higher.



## Glacier Mass Balance Simulation and Retreat Modelling for 101 Glaciers (M3)

Glacier mass balance is calculated using a distributed mass balance model that is described in Machguth and others (2009). The model is a simplified energy balance model, which runs at daily time steps and uses gridded RCM data of 2 m air temperature ( $T$ ), precipitation ( $P$ ) and total cloudiness ( $n$ ) for input. Because of spurious values in the daily RCM fields the data applied here are of monthly resolution. Daily values are generated from linear interpolation and precipitation falls every fifth day (Salzmann and others, 2012). Cumulative mass balance  $b_c$  on day  $t + 1$  is calculated for every time-step and over each grid cell of the DEM according to Oerlemans (2001):

$$b_c(t + 1) = b_c(t) + \begin{cases} \Delta t \cdot (-Q_m)/l_m + P_{solid} & \text{if } Q_m > 0 \\ P_{solid} & \text{if } Q_m \leq 0 \end{cases} \quad (2)$$

where  $t$  is the discrete time variable,  $\Delta t$  is the time step,  $l_m$  is the latent heat of fusion of ice ( $334 \text{ kJ kg}^{-1}$ ) and  $P_{solid}$  is solid precipitation in meter water equivalent (m w.e.). The energy available for melt ( $Q_m$ ) is calculated as follows:

$$Q_m = (1 - \alpha)S_{in} + C_0 + C_1T \quad (3)$$

where  $\alpha$  is the surface albedo (three constant albedo values are applied: snow = 0.72, firn = 0.45 and ice = 0.27),  $S_{in}$  is the incoming shortwave radiation at the surface, being calculated according to Greuell and others (1997) from  $n$  and clear sky global radiation computed at DEM resolution and taking all effects of exposition and shading into account. For  $T$ , the unit is  $^{\circ}\text{C}$ , and  $C_0 + C_1T$  is the sum of the longwave radiation balance and the turbulent exchange (Oerlemans, 2001).  $C_1$  is set to  $12 \text{ W m}^{-2} \text{ K}^{-1}$  and  $C_0$  is tuned to  $-45 \text{ W m}^{-2}$  (cf. Machguth and others, 2009). Accumulation equals  $P_{solid}$ , the redistribution of snow is not taken into account, and a threshold range of 1 to  $2^{\circ}\text{C}$  is used to distinguish between snowfall and rain. Any melt water is considered as runoff, i.e. refreezing and internal storage of melt water is neglected.

Glacier retreat is simulated based on the modelled mass balances and the so-called  $\Delta h$  glacier-retreat approach following Huss and others (2010b). The latter parameterizes glacier surface elevation change by distributing glacier mass loss or mass gain to the entire glacier surface according to altitude dependent functions of observed changes in glacier thickness. Here, we use the glacier size dependent  $\Delta h$  functions as proposed for the Swiss Alps (Huss and others, 2010b, Figure 3b therein). Glacier geometry is updated annually based on calculated surface elevation changes. Glacier surface mass balance is calculated on the updated topography and thus considers the mass balance-altitude feedback, i.e. a reduction in glacier thickness results in a lower elevation of the glacier surface and consequently a more negative mass balance (e.g. Raymond and others, 2005). Glacierized grid cells become ice-free when their elevation falls below the elevation of the glacier bed.

Simplifications in the used mass balance model (e.g. debris cover is not considered) limit the number of glaciers where reasonable mass balances can be calculated. Therefore, 101 glaciers are selected from the SGI1973 based on the following criteria: (a) no or little debris cover, (b) no or little influence of avalanches, (c) mass loss restricted to melting (the applied mass balance model does not consider any processes like calving into lakes or over rock faces), and (d) sufficient size ( $> 1 \text{ km}^2$ ) as small glaciers usually show accumulation patterns of a very local nature with strong influence of wind-drift and avalanching.

M3 is coupled with climate by using gridded RCM fields for model input, rather than projected temperature change at locations of weather station (cf. models M1 and M2). The direct use of the RCM fields basically involves the two steps of (a) downscaling the gridded 25 km resolution fields to the 100 m resolution of the mass balance model, and (b) the de-biasing of the downscaled RCM fields. These two steps are implemented in the MB-modelling set-up and directly applied to each RCM grid while the model is running. The downscaling of  $T$  and  $P$  is based upon interpolation of the RCM values with the subsequent application of simple subgrid parameterizations while  $S_{in}$  is computed from high resolution clear sky global radiation and attenuation from clouds derived from interpolated total cloudiness  $n$  (cf. Machguth and others, 2012, for full details).

The de-biasing of the RCM fields is done for each variable according to the method described in Machguth and others (2012): Biases in RCM values of  $T$  and  $n$  are established from comparison to observations at 14 high mountain weather stations in the Swiss Alps and spatial distribution of RCM precipitation is scaled to match the precipitation pattern of the Schwarb and others (2001) precipitation map. However, the accuracy of the downscaled and de-biased fields is limited as knowledge of real meteorological conditions at the glacier sites is imperfect. In particular the large uncertainties in observed high-mountain precipitation (Sevruk, 1997) hamper the de-biasing procedure and make it impossible to achieve a level of accuracy that would allow the calculation of accurate mass balances for each individual glacier. This issue is reflected in the successful model-calibration to observed melt during the summer period while at the same time winter mass balance strongly disagrees with measurements (cf. Machguth and others, 2009). We have approached these limitations by applying a calibration procedure where the MB-model is driven by the downscaled and de-biased RCM time series for the period 1970–2000 and precipitation is adjusted for each glacier individually to achieve a prescribed cumulative mass balance (Machguth and others, 2012). Choosing an appropriate value for the cumulative mass balance is challenging as available observations clearly divert: While Zemp and others (2008) report a mean cumulative mass balance of  $-13 \text{ m w.e.}$  for 9 Alpine glaciers, Huss and others (2010a,c) calculate  $-9 \text{ m w.e.}$  from a combined approach of modelling and observations. We decide to prescribe a cumulative mass balance of  $-11 \text{ m w.e.}$  which is in the middle of the two values. Furthermore all glaciers were calibrated to the same cumulative mass balance. This simplification had to be introduced because for most of the 101 selected glaciers no individual observational records are available. We are confident that the latter simplification does only marginally affect the calculated future glacier volumes: Salzmann and others (2012) applied the same model chain and showed that using alternative sets of non-uniform

cumulative mass balances in the calibration procedure has a negligible impact on future scenarios. The downscaled, de-biased and calibrated RCM data are subsequently used to run the MB-model over the entire scenario period.

## RESULTS

The simulated glacier area loss for all three models is illustrated in Fig. 4. For M1 the moderate scenario is displayed, with an ELA shift of 150 m until the first scenario period and a shift of another 200 m until the second scenario period. As this model is a two-dimensional simplification of a glacier it is limited to provide area changes (on the initial unchanged DEM values) with the lower ends of the glaciers simply cut off. This leads to glacier geometries with cropped ablation and unchanged accumulation areas. However, the visual comparison with the moderate M2 and the M3 E7m scenario is provided nevertheless.

→ **Fig. 4 (visualization) about here**

Models M2 and M3 additionally require the ice thickness distribution to calculate ice volume change as a combination of surface lowering and area reduction. The resulting patterns of glacier shrinkage seem to be closer to reality as with M1 for some glaciers, as the shrinkage is starting along the edges (where the ice is thin) at the lowermost elevations (where thinning is highest). The visual comparison of M2 and M3 in Fig. 4 and the quantitative comparison in Fig 6d indicates that the area loss in M3 is slightly faster than for M2.

The evolution of the area-elevation distribution (hypsoetry) for 10-year time steps and the three moderate climate scenarios is depicted in Fig. 5. While for model M1 the entire distribution including the maximum value is shifted upwards, model M2 shows a constant decrease at all elevations without a trend in the maximum. This is due to the implemented elevation feedback, i.e. large parts of the surface area shift to lower elevations (where melting is higher). When focusing on the 101 selected glaciers from M3 also for the other two models (Fig. 5, lower panel), the trends of the area distribution for M1 and M2 are the same as for the full sample. Interestingly, the hypsoetric changes of M3 are rather similar to M1 but with an overall stronger loss in area at higher elevations and a reduced loss at lower elevations. In contrast to M1 and M2 which work on 25 m resolution, M3 operates at 100 m resolution. Therefore, the initial glacier area between c/d and e are not exactly the same.

→ **Fig. 5 (hypsoetry) about here**

The four plots in Fig. 6 show the temporal development of the area loss (and volume loss for M3) during the 21st century for all three models (M1, M2, M3) and their different realizations corresponding to the different applied climate scenarios, the thickness uncertainty (M2) and the full sample vs. the 101 selected glaciers (M1, M2). The development of the relative area change along the various model pathways is to a large extent similar, but differences are visible as well. There is a spread of about 10-20% around the near future (2035) and of about 30-50% at the end of the century for the various model realizations in all four plots. Considering the simulations for the sample of the selected 101 glaciers, the general trend for all model realizations is the same: by the middle of the century the area loss is still moderate but increases sharply until the end

of the century, especially with M3 and the high temperature scenarios of M1. This is also reflected in the glacier hypsometry modelled by M3 (Fig. 5e), which shows a marked increase in hypsometric area loss in the second half of the model simulation.

→ **Fig. 6 (area/volume loss) about here**

In Fig. 6a the curves for the applied climate scenario realizations for M1 (section 3.1) with a first ELA shift of 150 m until the first scenario period and a further ELA shift of 100, 200 and 300 m after the first scenario period are shown (for all and the 101 glaciers) leading to a spread of the modelled glacier area of 40% at the end of the century (loss between 55 and 95% by 2100). There is no large difference between the curves for all or the 101 glaciers.

The 30% uncertainty in the glacier thickness (Fig. 6b) results in a spread of not more than 20% considering area loss as modelled with M2 for the three climate scenarios. The spread of the lines reproducing area loss according to the three different scenarios is much larger (about 40% around the second scenario period), whereby the high temperature scenario (+5.75°C temperature increase by 2100) results in an almost complete loss of glaciers (around 90%). The uncertainty in ice thickness ( $\pm 30\%$ ) has a non-linear impact on glacier retreat. With 30% thinner ice the extent of the reference thickness is reached 20 years earlier while 30% thicker ice gives only 10 additional years before this extent is reached. So differences in ice thickness estimations directly impact on the time scales of the scenarios, but might have a smaller effect on the remaining ice in 2100 than resulting from the uncertainties in temperature change (Fig. 6b and d).

In Fig. 6c the evolution of area and volume for the selected 101 glaciers as modelled with three scenario ensembles and with M3 are shown. The behaviour of the curves is rather similar, solely differing by the speed of area loss, resulting in a spread of about 20% at the second scenario period.

For the comparison in Fig. 6d all scenario runs for all three models for the 101 selected glaciers are displayed. It shows that the uncertainties introduced by different realizations of climate change are very similar until the first scenario period and rather large in the second scenario period. So model results increasingly deviate towards the future. The moderate scenarios of the three models (M1 mod., M2 mod. and M3 E7m) result in a total loss of glacier area between about 60 and 80% around the year 2100. In terms of area loss, the scenarios M1 mod., M2 high, M3 E4m and M3 E7m are close together, i.e. they do not differ by more than 15%. The area loss modelled by scenarios M1 low and M2 mod. but in particular with M2 low is rather slow compared to the other scenarios and can be seen as a lower boundary.

The variable curvature of the lines reveals interesting details about the speed of glacier shrinkage at various phases of the recession, largely depending on the remaining area covered by thick ice. A key aspect is that all curves will finally approach 0, i.e. glaciers are unable to stabilize their extent for the given scenarios of climate change. This behaviour is also visible in the hypsometric changes in Fig 5b, where the area loss (all glaciers) is relatively large between the initial and the first step, whereas in Fig. 5d there is not much difference between these two curves.

In contrast to M1 and M2 which have a fixed starting point in 1985, the model start of M3 is already at 1970. This is done to maximize the length of the calibration period. For the model comparison the earlier starting point of M3 is negligent, as the climate was more or less stable and according to M3 only 2.5% (15 km<sup>2</sup>) of the area and 5% (2.8 km<sup>3</sup>) of the initial volume were lost from 1970 to 1985.

## VALIDATION

For M3 (and all three ensemble scenarios) the cumulative mass balance for the time period 1970–2000 is calibrated to an overall mass loss of -11 m w.e., the mean calculated from the observed cumulative mass budget from Zemp and others (2008) (-13 m w.e.) and Huss and others (2010a,c) (-9 m w.e.) (Salzmann and others, 2012). Within this calibration period a model validation for M1, M2 and M3 would be possible, as corresponding and consistent glacier outlines for nearly all Swiss glaciers exist for 1973 and 2000 (SGI2000; Paul, 2007). In Table 1 area (and where available volume) of all model scenarios and the glacier inventories are displayed for a comparison in a quantitative manner. The observed area loss is -20% for all and -9% for the 101 glaciers. The M3 scenarios and the moderate and high M2 scenario do not differ by more than 5% from these values. The cumulative mass budgets for the M3 scenarios are calibrated, but the value obtained for the high M2 scenario for all glaciers corresponds rather well to the observations (Paul and Haeberli, 2008). Cumulative mass budgets for the moderate M2 scenario is rather in the range of the value from Huss and others (2010a,c). Area (and volume) loss for M1 and the low M2 scenario are probably too low. This is expected for M1, where only the lower most parts of the glaciers were removed according to an AAR<sub>0</sub> of 60%. As many of the lower parts of the larger glaciers in 1973 ended in narrow tongues, only minor parts of the area are deleted.

→ **Table 1 (validation) about here**

In Fig. 7 a comparison of observed and modelled glacier extent for the year 2000 is shown for the glaciers in the Bernina region as an example. However, it has to be kept in mind that M1 and M2 are designed to model glacier evolution on a regional scale rather than for individual glaciers and that only three time steps are applied until 2000. As can be seen, the changes in the observed glacier extents (1973–2000) for the large glaciers occur at the snout and along the edges. Some glaciers show a distinctive retreat of the tongue from 1973 to 2000, but in general all glaciers lost area all over their margins due to the implemented surface lowering.

→ **Fig. 7 (validation 2000) about here**

For the glaciers depicted in Fig. 7, both, M2 and M3 reproduce the observed inward shift of glacier boundaries due to surface lowering well. The agreement between observed and modelled terminus positions of Tremoggia, Tschierva and Morteratsch glaciers is rather good, while the modelled retreat for Palü and especially Roseg glacier is too small (Fig. 7). Generally, the area and in particular the volume loss as modelled with M3 is larger than with M2, as already mentioned before (Fig. 4–6).

This is also illustrated in the inset map of Fig. 7. It shows the tongue of Tschierwa glacier with the outlines for the year 2000 as modelled by all models (and scenarios). M1 shows the typical pattern resulting from the cutting off the lower most part of the tongue, with a retreat of about -200 m compared to the mapped glacier outline, while the other two models achieve a similar glacier outline as the mapped tongue position.

## DISCUSSION

### Simplifications and Uncertainties

Concerning the glacier change models and the climate change scenarios several simplifications and uncertainties need to be discussed. Although there is general agreement concerning the temperature development in the climate models used, changes in precipitation are highly uncertain and do not show a significant trend (e.g. Bosshard and others, 2011). They are only considered in M3 and have been neglected for M1 and M2. A further simplification in M1 is that all glaciers have the same temperature sensitivity (150 m ELA rise per °C), response time (50 years) and AAR<sub>0</sub> (60%) as discussed in section 3.1. Apart from the response time, these values are typical mean values that certainly differ from glacier to glacier. Response time is somewhat biased towards larger glaciers, but this is required as they are the main contributors to the overall area and volume change and should thus not shrink too fast. The parameterization of M2 is based on three linear extrapolations of an observed trend (elevation change in response to a 1°C increase) and all glaciers follow the same elevation dependent thickness loss, using an empirical generalization rather than a regression. The three assumed time periods for glacier surface adjustment constitute a best guess to cover three scenarios for M2. The underlying climate scenarios of M3 are based on RCM-simulations (ensemble means) and are thus beyond a simple linear extrapolation. On the other hand, M3 is restricted to a subsample of selected glaciers that adhere to specific criteria (section 3.3) to be suitable for the applied mass balance model. Both models, M2 and M3, are based on a modelled ice thickness distribution with an estimated uncertainty of about ±30% that directly impacts on the time-scale of the modelled glacier retreat.

We have not explicitly assessed the impact of all simplifications mentioned above on glacier evolution. In general, many of the effects will average out when large samples are considered, as deviations from the mean values used are probably normally distributed (apart from the response time bias mentioned above). The hypothesis is not explicitly tested, but for natural systems and large samples of independent data deviations from a mean are normally distributed. For individual glaciers the differences of the here-modelled development to a model that considers glacier characteristics more explicitly can be large. However, for regional-scale assessment these differences are expected to mainly contribute to the variability rather than to the trend and both are governed by the implemented climate scenario.

All model approaches investigated here have their advantages and disadvantages and were designed for specific research questions. All three models operate on a regional scale, but M3 is already rather glacier-specific. As a governing principle, a balance between computational effort and the required level of detail in the results has to be found.

## Possibilities and Limitations for Model Applications

For a sound model intercomparison the models can only be compared against observed changes in the past. As the model starting point is 1985 for M1 and M2 and 1970 for M3, there is only a short time period available for a comparison. This comparison might not really be seen as a validation, as all models are not expected to provide useful results over this timescale. However, for the year 2000 modelled glacier extents fit to the mapped ones rather well. As the modelled future changes are much larger than the changes observed over this 15 year period, the significance of this comparison is limited.

The modelled area losses (Fig. 6) clearly reflect the temperature trends of the applied climate scenarios (Fig. 2). The three moderate scenarios that prescribe a  $2/4^{\circ}\text{C}$  temperature increase for the two scenario periods centred around 2035 and 2085, show a comparable area loss over time (with a maximal spread of about 20%). The spread in area loss of about 50% by 2100 is given by the low temperature scenario of M2 (upper boundary) and the E2m scenario from M3 (lower boundary).

M1 and M2 are highly simplified models, but provide glacier change scenarios for large glacier samples at a regional scale with a small computational effort. This is in contrast to M3 that better considers characteristics of individual glaciers. Though the simplifications in M1 and M2 are substantial, they might be considered as being compliant with the uncertainties of the RCM scenarios, i.e. the variability in area change introduced by the simplifications are in the same order of magnitude as those resulting from the unknown future climate. According to the results of this comparison, the latter are somewhat larger. For studies seeking to establish future trends in the glacier cover of entire mountain ranges (e.g. the Swiss Alps), M1 and M2 are fast approaches providing results similar to the more detailed modelling with M3. As both models apply average parameter sets to all Swiss glaciers, the results are valid on the sample as a whole. We also found agreement with results from completely different studies (Huss and others, 2010b; Huss, 2012; Juvet and others, 2009, 2011), which is not surprising as the strong future temperature increase is dominating the response. The rather simple approach of M1 was designed to provide adjusted glacier areas as an input for hydrological models operating at a regional scale (e.g. Viviroli and others, 2009; Köplin and others, 2012). This study has shown that area loss is fastest in M1 which can be seen as a lower bound time scale for the expected terminus retreat. For the hydrological model that generates additional runoff solely from the change in glacier area, the stronger area change in M1 might be well suitable to mimic the expected future increase in runoff due to downwasting, a process that is not included in M1 but important in reality.

Although all three models are based on equivalent climate scenarios and RCM runs, the coupling to the climate model output is rather different: retrospective with M1, based on trend extrapolation with M2, or directly driven by RCM-grids

in M3. The modelled future development in glacier extent with the moderate scenarios can already be seen as lower bound estimates, as the current temperature increase is already stronger and modelled mean annual thickness loss from 2000 to 2010 (with M2 mod. and M3 E7m, Fig. 8) is only -0.4 m/year according to the models instead of the observed -0.8 m/year (Zemp and others, 2009). The decrease in mean annual thickness change at the last part of the modelling period for all scenarios in M3 (Fig. 8) can be related to the direct coupling with RCM data (allowing for positive and negative mass balances) and a possible future adjustment of the remaining small glaciers at high elevation.

→ **Fig. 8 (thickness loss) about here**

Finally, it has to be considered that several feedbacks are not incorporated in any of the models, including the change of albedo (Oerlemans and others, 2009), development of new lakes (Frey and others, 2010), increasing debris cover (Jouvet and others, 2011) or the warming of yet cold or polythermal ice bodies (Vincent and others, 2007; Hoelzle and others, 2011). The local and general influence of these processes is difficult to be assessed because they partly act in opposite directions.

## CONCLUSION

The three compared approaches for calculating future glacier evolution are using robust (based on simple physical laws or observations) but simplified parameterizations that are applicable to large glacier samples. Two of the models are implemented in a GIS processing environment and enable glacier-change scenarios to be simulated at a regional scale with small computational costs. From the comparison of the three models we conclude the following:

The moderate scenarios of the three models give a relative area loss between 60 and 80% by 2100 compared to the glacier extent in 1985; in reality glacier vanishing could be even more rapid.

Due to the simplifications induced by the parameterization schemes, uncertainties are large at a local scale (individual glaciers), but likely average out at the regional scale (Swiss Alps) and over extended time periods (decades to a century).

The overall trends of the modelled future glacier evolution - a strong to almost complete loss of glaciers by the end of the 21st century - are therefore clear and robust as air temperatures are expected to increase further.

The variability in the climate scenarios leads to a maximum spread of about 40% in the remaining area by 2100 (relative loss between 55 and 95%).

The uncertainty in estimations of present-day ice thickness (about  $\pm 30\%$ ) has a smaller but still considerable effect and impacts directly and non-symmetrically on the time scale of the modelled future glacier development.



The probably strong impact of unconsidered feedback processes (albedo change, lake formation, subglacial ablation, debris cover, etc.) needs further investigation.

All three models have advantages and disadvantages in their application. Which model to choose for a specific application depends on data availability and the level of detail required in the output. M1 and M2 have proven to provide fast and robust first order estimates for glacier retreat dominated by temperature increase. They might be less suitable when changes in precipitation have to be considered as well, but here the uncertainties are even much larger.

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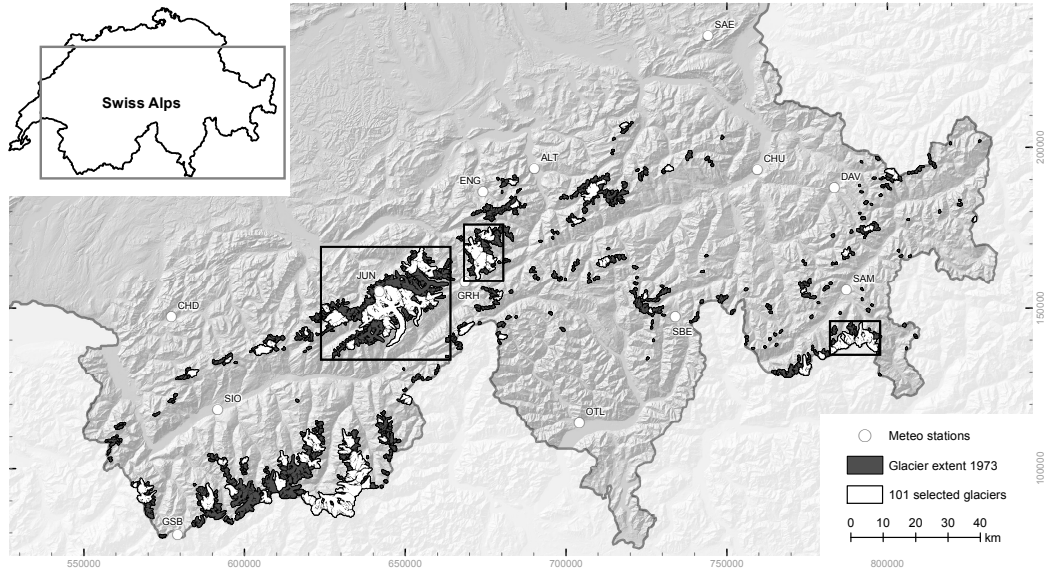
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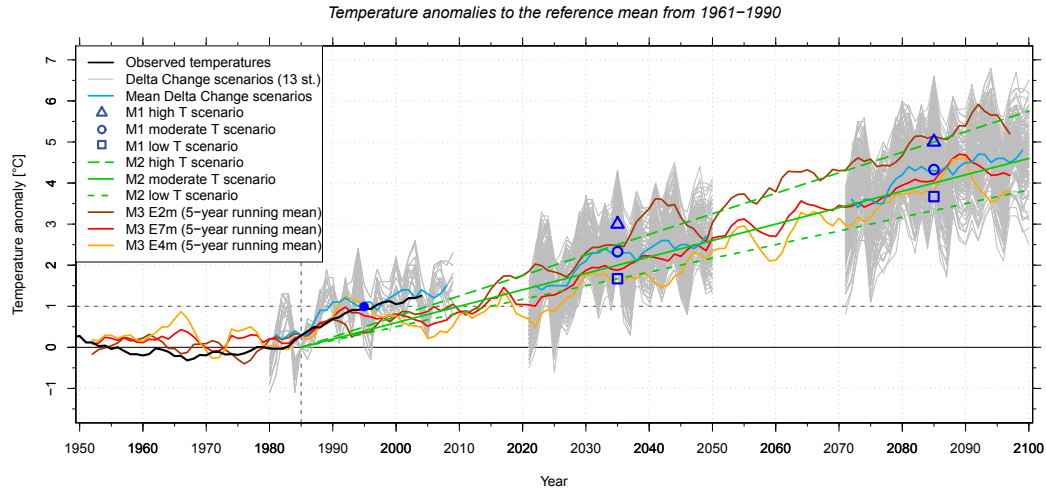
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**Table 1.** Comparison of area and volume loss and cumulative mass budgets (cum. mb) for all scenarios of M1, M2 and M3 from their model start until the validation year 2000 together with the derived area loss obtained by comparing the two relevant Swiss Glacier Inventories (SGI) from 1973 and 2000 for the two samples all Swiss glaciers and the selected 101 glaciers. (\* The indicated cumulative mass budgets for the "SGI all" refers to the DEM differencing from Paul and Haeberli (2008) and the ice thickness modelling of Linsbauer and others (2012))

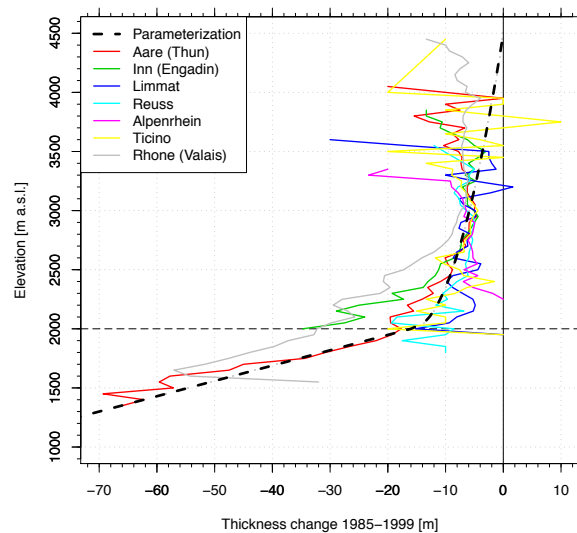
	Area		Volume		cum. mb	time
	%	km <sup>2</sup>	%	km <sup>3</sup>	m w.e.	periode
M1 all	-5	-61	–	–	–	1985-2000
M1 101	-3	-19	–	–	–	1985-2000
M2 low all	-13	-176	-8	-6.4	-5.6	1985-2000
M2 low 101	-5	-31	-6	-3.1	-5.1	1985-2000
M2 mod. all	-15	-202	-10	-7.6	-7.4	1985-2000
M2 mod. 101	-6	-36	-7	-3.7	-6	1985-2000
M2 high all	-19	-249	-13	-9.9	-10.1	1985-2000
M2 high 101	-7	-47	-9	-5.0	-8.6	1985-2000
M3 E4m 101	-6	-38	-13	-6.8	-11.0	1970-2000
M3 E7m 101	-6	-39	-12	-6.7	-11.0	1970-2000
M3 E2m 101	-7	-42	-12	-6.3	-11.0	1970-2000
SGI all	-20	-268	–	–	-11*	1973-2000
SGI 101	-9	-56	–	–	–	1973-2000



**Fig. 1.** The model domain 'Swiss Alps' with the marked subsample of 101 selected glaciers. The white points denote the locations of the MeteoSwiss weather stations with homogenized annual mean temperature data for the period 1980–2009 (station altitude in m.a.s.l. is given in parenthesis) ALT: Altdorf (438), CHD: Chateau-d'Oex (985), CHU: Chur (556), DAV: Davos (1594), ENG: Engelberg (1035), GRH: Grimsel Hospiz (1980), GSB: Col du Grand St Bernhard (2472), JUN: Jungfrauoch (3580), OTL: Locarno/Monti (366), SAE: Säntis (2502), SAM: Samedan (1708), SBE: S. Bernardino (1638) and SIO: Sion (482). Black rectangles show the extent for Fig. 4 and 7.

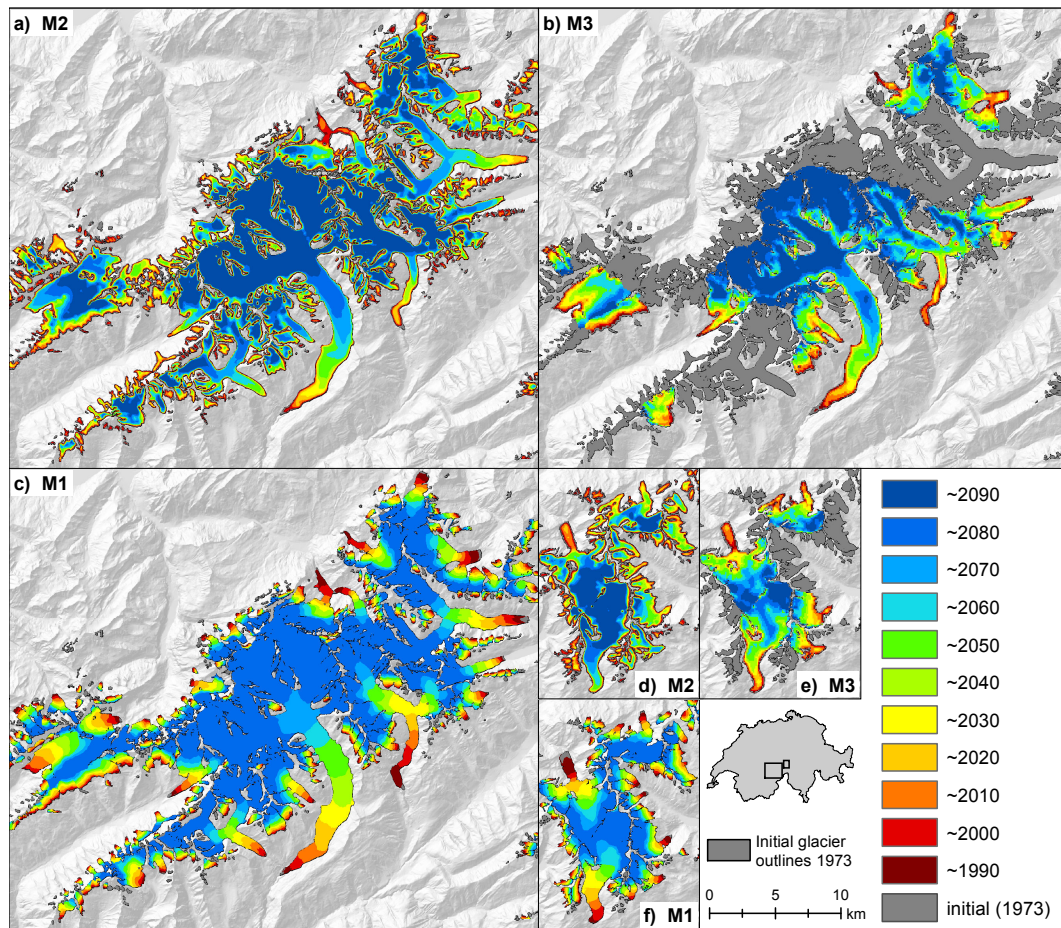


**Fig. 2.** Anomaly of 2 m air temperature of the observed temperatures and climate scenarios used, all normalized to the reference period from 1961–1990 for Switzerland after Rebetez and Reinhard (2008). As a reference, the annual temperature anomalies (Rebetez and Reinhard, 2008) from 12 homogenized temperature series for 12 stations in Switzerland (Begert and others, 2005) are displayed in black. The gray lines show observed temperatures from 13 MeteoSwiss weather stations (cf. Fig. 1) for the control period 1980–2009 and their projections to the two scenario periods 2021–2050 and 2071–2100 according to the delta change values and ten different model chains from Bosshard and others (2011). In light blue the five year running mean for the measurements and the projections for the 13 weather stations are shown. The blue point is the starting point for all three M1-scenarios and the triangle, circle and square mark the low, moderate and high temperature scenario for M1. In green the lines of the linear extrapolated temperature trends as used for M2 are shown and in orange, red and brown the five year running mean for three scenario ensembles E2m, E7m and E4m as used for M3.

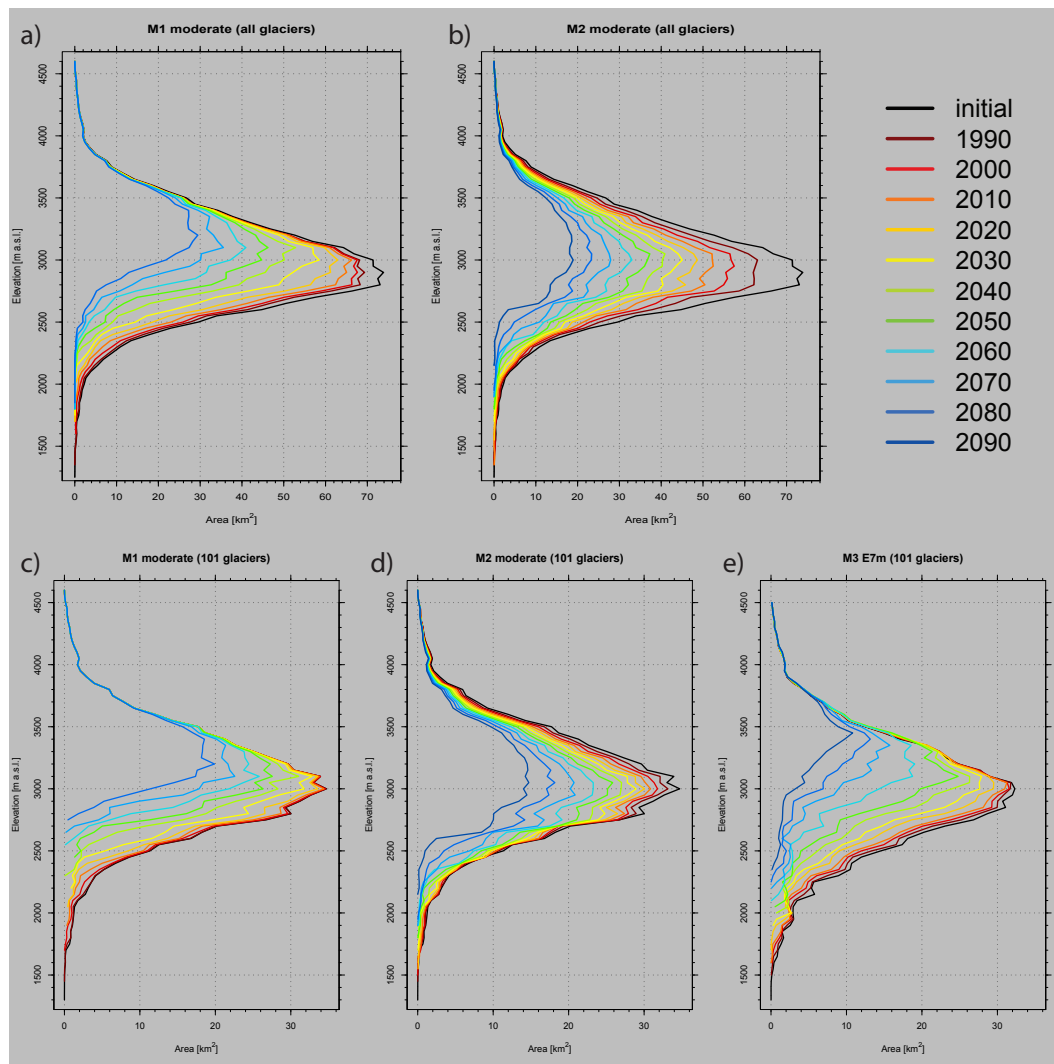


**Fig. 3.** Thickness changes from 1985 to 1999 (Paul and Haeberli, 2008) for seven major river catchments together with an empiric elevation dependent function to parameterize the thickness loss for all Swiss glaciers in model M2 (cf. eq. (1)).

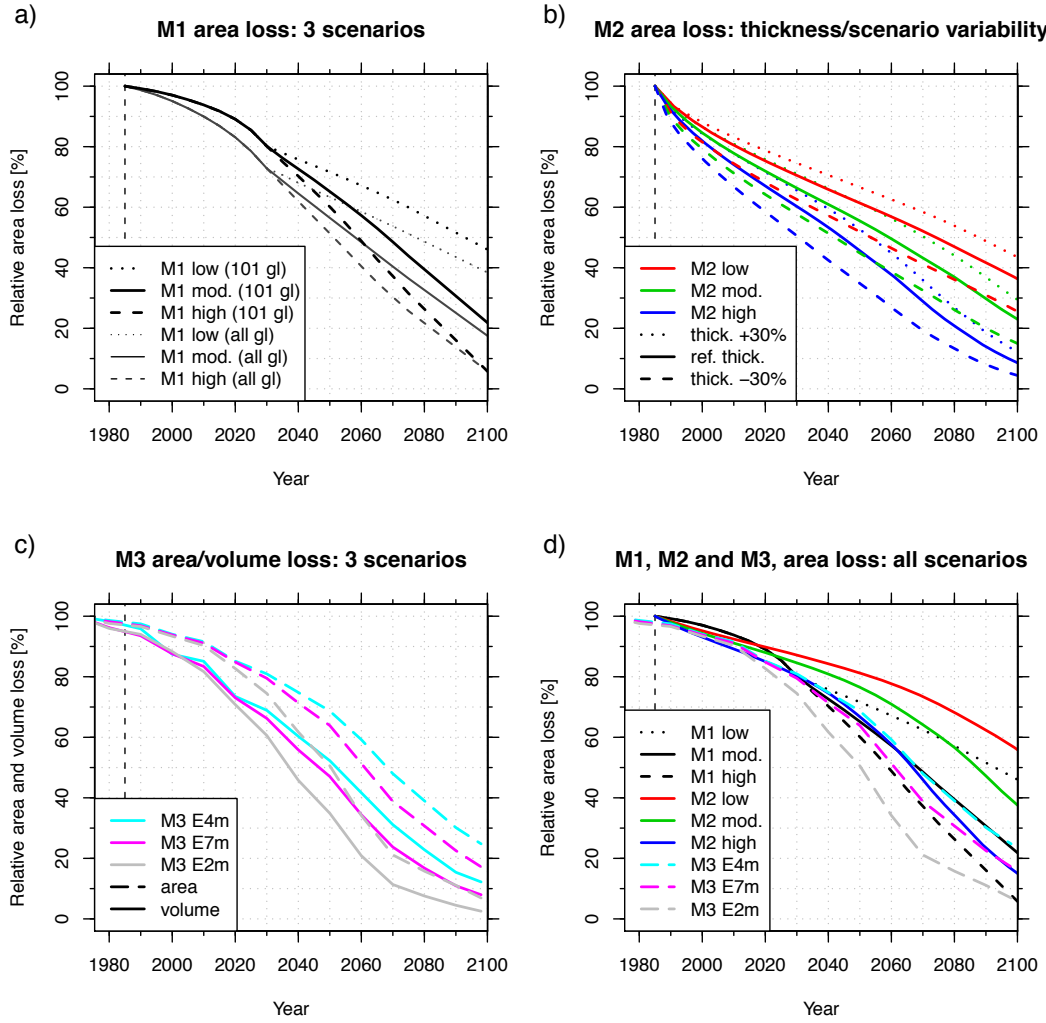




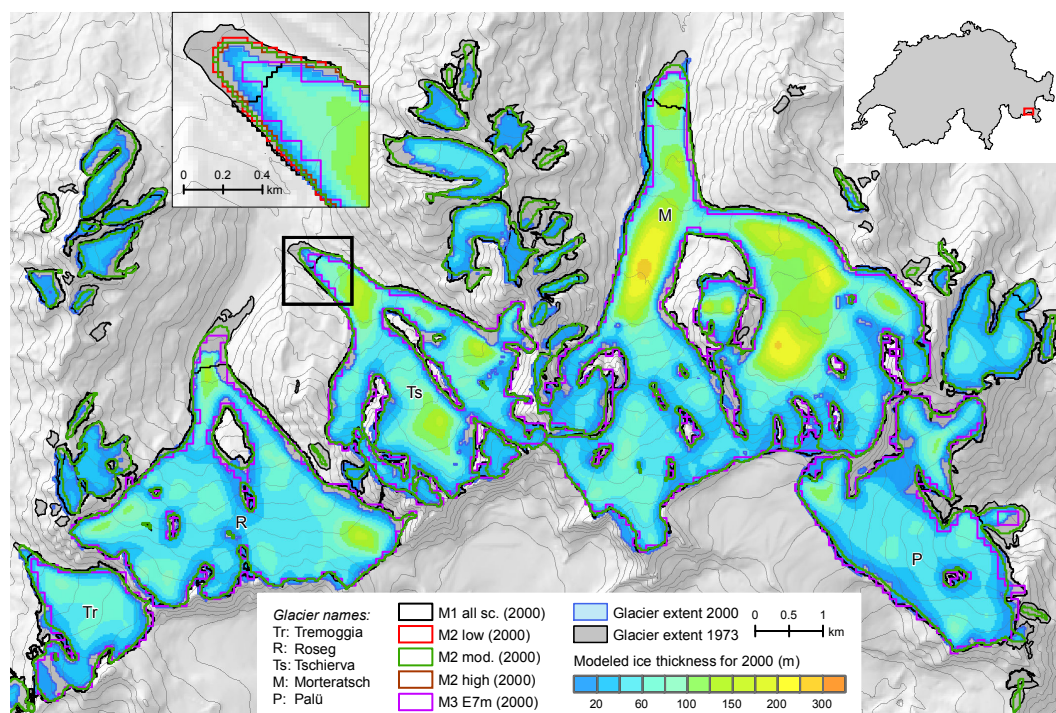
**Fig. 4.** Visualization of the results for the regions around Aletsch (a-c) and Rhone (d-f) glaciers for all three models (M1: c/f, M2: a/d, M3: b/e) with their moderate climate scenario, starting with their 1973 extent (i.e. 1985 DEM). The colour steps depict 10 year changes and are the same for all models. The modelling with M3 was restricted to a subsample of 101 glaciers.



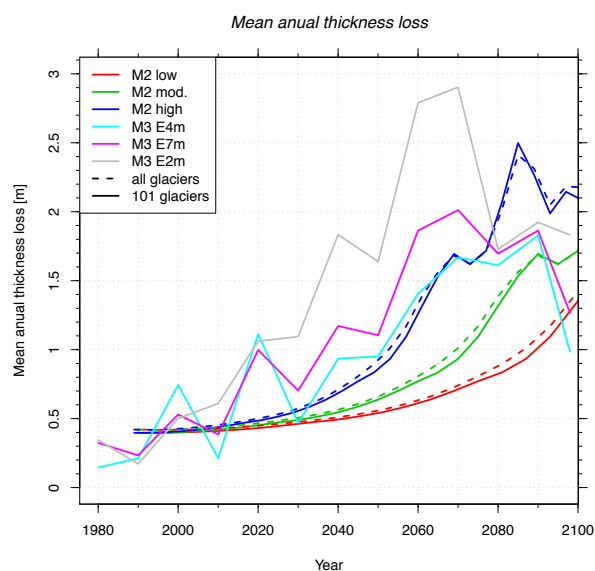
**Fig. 5.** Change in overall glacier hypsometry in 10 year steps (colour code is the same as in Fig. 4) until 2090 (2080 for M1) for all glaciers (a, b) and the 101 selected glaciers (c, d, e), calculated with the moderate temperature scenarios of M1 (a, c) and M2 (b, d) and the ensemble scenario E7m from M3 (e), respectively.



**Fig. 6.** Development of relative area loss from the model starting point (1985 for M1 and M2; 1970 for M3) until 2100 for all three models and their different realizations (scenarios, thickness, glacier samples). a) The three retrospective applied scenarios for M1 represented by the gray lines for all glaciers and in black for the 101 glaciers. b) The three different temperature trend extrapolations applied in M2 together with the corresponding  $\pm 30\%$  uncertainty due to the ice thickness modelling for all Swiss glaciers. c) Area and volume loss for the selected 101 glaciers as modelled with the three climate scenario ensembles used in M3. d) A comparison based on the sample of the selected 101 glaciers of the climate scenario runs from all three models.



**Fig. 7.** The extents of the glacier in the Bernina region according to the inventories from 1973 and 2000 and the modelled ice thickness for the year 2000 according to Linsbauer and others (2012) compared to the modelled area evolution with the moderate scenarios of M1, M2 and M3 for the time step corresponding to the year 2000. The inset shows the Tschierva glacier snout with all the glacier margins according to all model scenarios.



**Fig. 8.** Mean annual thickness loss over time as derived from the three scenarios of M2 and the three ensemble means of M3.